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TDR Calibration for the Alternative Landfill Cover Demonstration (ALCD)

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Prepared by
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Abstract

The Alternative Landfill Cover Demonstration is a large scale field test that compares the performance of various landfill cover designs in dry environments. An important component of the comparison is the change in the moisture content of the soils throughout the different cover test plots. Time Domain Reflectometry (TDR) is the primary method for the measurement of the volumetric moisture content. Each of the covers is composed of layers of varying types and densities of soils. The probes are therefore calibrated to calculate the volumetric moisture content in each of the different soils in order to gain the optimum performance of the TDR system. The demonstration plots are constructed in two phases; a different probe is used in each phase. The probe that is used in Phase I is calibrated for the following soils: compacted native soil, uncompacted native soil, compacted native soil mixed with six percent sodium bentonite by weight, and sand. The probe that is used in Phase II is calibrated for the following soils: compacted native soil, uncompacted native soil, and sand. In addition, the probes are calibrated for the varying cable lengths of the TDR probes. The resulting empirically derived equations allow for the calculation of in-situ volumetric moisture content of all of the varying soils throughout the cover test plots in the demonstration.

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Introduction

The effectiveness of current EPA landfill cover designs is being questioned, especially in the southwestern states of the United States. The Alternative Landfill Cover Demonstration is a large scale field test to determine the effectiveness of the current accepted designs and compare the results to those of alternative landfill cover designs. The purpose of the demonstration is to determine which cover is the most effective based on cost, ease of construction, and performance. One of the variables being compared in the performance area is the moisture content of the soils in the covers. Time domain reflectometry (TDR) probes measure the moisture content of the soils in each cover. However, an extensive calibration of the probes is required before useful data can be obtained from the probes. Once the calibration is complete, TDR probes provide a means of measuring in-situ volumetric moisture content of soils which allows for a thorough comparison of the various landfill covers.

The following report describes the procedure that is used to calibrate all of the TDR probes used in the Alternative Landfill Cover Demonstration.

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Background

The Alternative Landfill Cover Demonstration (ALCD), currently underway at Sandia National Laboratories in Albuquerque, New Mexico, is a large scale landfill cover field test. In the demonstration, six landfill cover test plots are constructed side-by-side to compare the plots based on their respective costs, ease of construction, and performance. The construction of the plots is divided into two phases. In Phase I, two covers meeting minimum RCRA Subtitle 'C' and Subtitle 'D' requirements, respectively, are constructed along with Alternative Cover Number one, designed for dry environments. In Phase II, Alternative Covers Two, Three, and Four, which are specifically designed for dry environments, are constructed. The Subtitle 'C' and Subtitle 'D' plots serve as a baseline to compare against the alternative designs in Phase I and Phase II. The results of the field test indicate which of the landfill cover designs is most effective for dry environments.

While the designs of the covers differ, the size and test conditions are the same for all of the test plots. Each of the plots is one hundred meters long and thirteen meters wide; all plots are separated by eleven meters. The plots are situated lengthwise along the east-west axis. Each cover slopes five percent from the middle of the plot fifty meters to the ends of the plot; the layers within each cover design have the same five percent slope. The orientation of the plots allows for passive and active monitoring of the test plots. The western slopes of the plots are monitored under ambient conditions - passive monitoring. A sprinkler system installed in the eastern slopes of the plots allows for stress tests (i.e., simulation of a one hundred year storm) - active monitoring. The similar conditions of the plots allows for an equitable comparison of the cover designs.

All test cover plots are instrumented to quantify water balance variables and ancillary information. For example, various instrumentation installed in and around the covers allows for the continuous collection of the following data: soil moisture status, percolation and interflow, runoff, precipitation, wind speed and direction, relative humidity, and air and soil temperature. The data collection system is automated with manual backup for each individual instrumentation system. Also, periodic measurements will be obtained on vegetation cover, biomass, leaf area index, and species composition. The collection of all such data is tantamount in making a comprehensive comparison of the covers.

The success of the demonstration is heavily dependent on the monitoring systems and care taken prior to and during their installation; as well as follow-on maintenance. One example of care taken prior to the installation is the calibration of the Time Domain Reflectometry (TDR) probes used to determine soil moisture status. TDR is the process of sending pulses through a cable and observing the reflected waveform. If a waveguide, such as a steel rod, is placed on the end of a cable, the reflected waveform is influenced by the dielectric constant of the material surrounding the waveguide. In soils, the dielectric constant of the soil is greatly influenced by the amount of water in the soil; therefore, the reflected waveform from a TDR probe in soil is altered by the moisture content of the soil. The dielectric constant of the soil can be related to the volumetric water constant of the soil in a mathematical expression; thus, a TDR probe can be used to determine in-situ soil moisture content. However, the probes must be carefully calibrated before they are installed. Different types of soils reflect different waveforms at similar moisture contents. Therefore, a careful calibration of the TDR probes is required before the probes are installed in the test plots in order to ensure the high level of performance required from the monitoring system.

Soil Measurements With Time Domain Reflectometry

Soil moisture measurements are made using TDR, a process of sending pulsed waveforms through a coaxial cable to a fixed length probe and observing the reflected waveform. The reflected waveform is analyzed for two distinct points: the beginning of the probe and the end of the probe. The distance between the two points is identified as the apparent length of the probe (See Figure 1). The apparent length of the probe is proportional to the square root of the apparent dielectric constant of the soil. Because the dielectric constant of water is relatively high in comparison to other medium, a signal will propagate slower in a wetter media (i.e., soil) than in the same medium when dry; therefore, probes in soils with a high moisture content have a longer apparent length than do probes in drier soils. Further, a mathematical relationship between the volumetric moisture content of the soil and the apparent probe length obtained from the waveform can be established. The resulting equation provides a tool for in-situ volumetric soil moisture content measurements using a time domain reflectometry system.

The TDR system that is used in the Alternative Landfill Cover Demonstration (ALCD) consists of Sandia designed and built probes in conjunction with Campbell Scientific's TDR Soil Moisture System for Phase I. Phase II of ALCD uses Campbell Scientific designed and built TDR probes in conjunction with the same CR10 system.

The main components of Campbell Scientific's TDR Soil Moisture System are a Tektronix 1502B cable tester and a CR10 measurement and control system. The use of the 1502B in conjunction with the CR10 allows for the greatest flexibility in the TDR system. The CR10 contains several different algorithms for wave analysis. For example, the CR10 can measure and store entire waveforms, electrical conductivity, or the ratio of apparent length to actual length of the probe. For demonstration purposes, the CR10 is programmed to output the ratio of the apparent length of the rods to the actual length of the rods (L_a/L); volumetric moisture contents are calculated from the ratio in a separate algorithm.

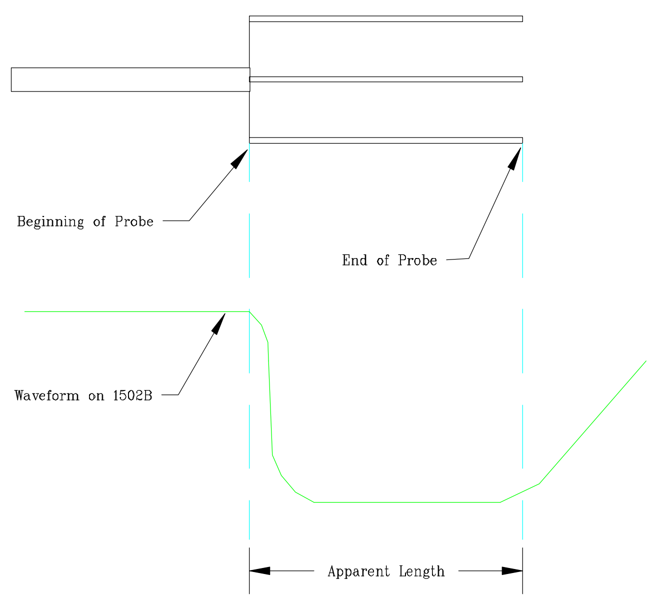

Figure 1. Apparent Length of TDR Probe

The TDR probes for Phase I are a product of extensive research conducted at Sandia National Laboratories. During the design of Phase I, commercially available probes reflect a waveform that can not be used. The waveform does not show a rise when the signal reaches the end of the probe; therefore, the end point of the wave can not be determined and a new probe is required. Components of the probe, such as rod length, rod spacing, number of rods (two or three), coating the rods (with several different types of coatings, coating thickness, and surface preparation), rod diameter, and diode installments are varied until the optimum probe is developed. The resulting probes consist of a potted PVC housing with a length of RG-8 coax cable connected to three equally spaced, six inch long exposed length, epoxy coated prongs (See Figure 2). The center prong is connected to the signal propagating conductor, while the two outside prongs are connected to the coax shield. The epoxy coating inhibits conductivity arising from saline conditions in highly compacted, wet soils. This condition greatly reduces the amplitude of the signal, making meaningful measurements of the time domain difficult to obtain which is a problem in the commercially available probes.

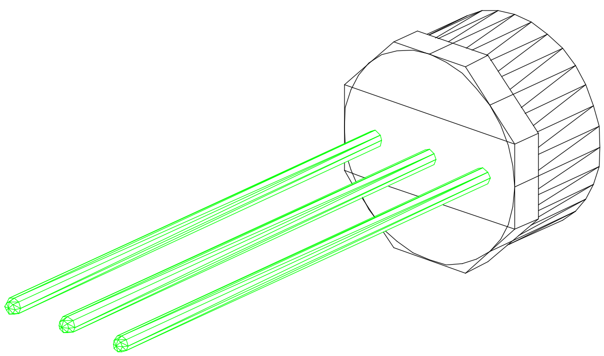

Figure 2. Phase I TDR Probe

When Phase II is in the design phases, Campbell Scientific releases a TDR probe that is capable of reflecting waveforms in the various soils used in the Phase II test plots. In order to conserve the resources used in constructing more probes, the TDR probes for Phase II are designed by and purchased from Campbell Scientific (See Figure 3). The probes consist of a length of RG-8 coaxial cable terminating in an epoxy body. Within the epoxy body, the center conductor of the cable is connected to the center rod of the three parallel 3/16 inch diameter, twelve inch long stainless steel rods. The shield of the coaxial cable is attached to the two outside rods. The rods on the Campbell Scientific probes are not coated due to the increased resolution of the longer rods and the lack of sodium bentonite in the soils producing better defined waveforms.

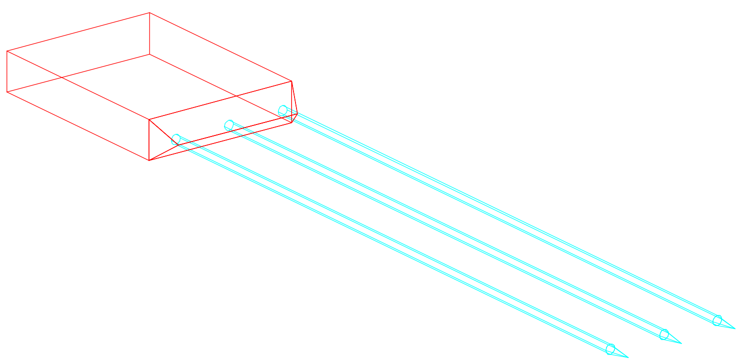

Figure 3. Phase II TDR Probe

Phase I Data Collection

Various external variables may alter the CR10's analysis of the waveform; therefore, the calibration process requires that the most significant variables be identified and accounted for in the procedure. After several preliminary measurements, two variables are identified to have the greatest impact on the waveform and the CR10's analysis: soil type and cable length. The TDR probes for ALCD, Phase I are placed in four distinct soils: compacted soil mixed with 6% bentonite (by weight), sand, compacted native soil and uncompacted native soil. The CR10 records a different L_a/L ratio for similar moisture contents; therefore, calibration data is collected for each of the different soils in Phase I. Furthermore, the total cable length of each probe affects the waveform and the resulting L_a/L value. After examining the cable lengths that are required for the various soil types in each plot, five cable lengths are identified to adequately represent the entire array of cable lengths; therefore, coaxial cables are prepared to allow for the following lengths: 59', 82', 98', 120', and 138'. In the resulting calibration procedure, data is collected for each of the five cable lengths within each soil type.

To achieve proper soil compaction, a customized mold is designed and manufactured. The mold is similar to a Proctor mold; however, the diameter of the mold is 7.75 inches, and the height is 5.25 inches. Also, a fitting for a TDR probe is built into the mold. The fitting holds the PVC housing of the TDR probes in place while soil is compacted around the probe rods in the mold. The fitting prevents any probe movement and prevents damage that would occur to the probe rod coating if the probe is forced into a compacted brick of soil. A thin PVC pipe is cut to fit within the mold and around the probe. The PVC pipe prevents the metal mold from altering the TDR signal. The custom mold allows for similar compaction and soil conditions to be achieved throughout the entire calibration procedure.

6% Bentonite Soil and Compacted Native Soil

Throughout the calibration procedure, representative field conditions are simulated. Therefore, samples of each of the soils are taken from their respective stockpiles at the construction site and are sieved with a number 4 sieve. The resulting soil is then placed in the mold with four equal lifts. The customized mold is approximately twice the size of the standard Proctor mold; therefore, each lift is delivered 56 blows, more than twice the amount required for a standard Proctor test, with a standard Proctor Compaction hammer. The TDR probe is placed in the mold between the second and third lifts. Once compaction is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. While ten L_a/L values are recorded by the CR10, the soil sample is weighed. Once the ten values are collected, the soil sample is broken apart, and a sample of soil is taken from around the probes and dried to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil is mixed again to achieve a homogeneous sample. The procedure is repeated for five different gravimetric water contents ranging from 1.4% to 18%. After ten L_a/L values are obtained for each of the five different water contents, the cable length is changed and the procedure is repeated for each of the five different cable lengths.

Uncompacted Native Soil

A similar procedure is repeated for the uncompacted native soil. Samples of soil are taken from the stockpile in the field and sieved with a number 4 sieve. The TDR probe is secured into the mold while the soil is placed in the mold and slightly compacted at varying intervals. An inconsistent procedure of compaction simulates field conditions. Once "compaction" is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. Ten L_a/L values are recorded by the CR10, and then the soil sample is weighed. The soil sample is then broken apart, and a sample of soil is taken from around the probes and is dried to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil is mixed again to achieve a homogeneous sample. The procedure is repeated for five different gravimetric water contents ranging from 1.4% to 18%. When L_a/L values are obtained for the five different water contents, the cable length is changed and the procedure is repeated for the five different cable lengths.

Sand

Samples of sand are also taken from the stockpile in the field. The TDR probe is secured into the mold while the sand was placed in the mold and slightly compacted at varying intervals. An inconsistent procedure of compaction is used to simulate field conditions. Once compaction is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. Ten L_a/L values are recorded by the CR10, then the soil sample is weighed. A sample of soil is taken from around the probes and dried to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil is mixed again to achieve a homogeneous sample. The procedure is repeated for five different gravimetric water contents ranging from 1.4% to 18%. When L_a/L values are obtained for the five different water contents, the cable length is changed and the procedure is repeated for the five different cable lengths.

Phase II Data Collection

As in Phase I, soil type and cable length are the most significant variables in affecting the CR10's analysis of the waveform. Therefore, data is collected for the three types of soils in Phase II: sand, compacted native soil, and uncompacted native soil. Also, data is collected for five representative cable lengths, 85, 102, 119, 138, and 156 feet, for each type of soil.

In order to achieve proper compaction of the soil, a mold is designed and built at Sandia National Laboratories to accommodate the larger Phase II probe. The mold is constructed from a one quarter inch steel plate with the following dimensions: 9 inches wide by 24 inches long by 6 inches deep. This size mold allows the entire Phase II probe to lie flat; consequently, a fitting is not required to hold the probe in place. Soil is compacted around the entire probe within the mold.

Sand

Samples of sand are also taken from the stockpile in the field. The TDR probe is secured into the mold while the sand is placed in the mold and slightly compacted at varying intervals. An inconsistent procedure of compaction is used to simulate field conditions. Once compaction is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. Ten L_a/L values are recorded by the CR10, then the soil sample is weighed. A sample of soil is taken from around the probes and is dried in order to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil was mixed again to achieve a homogeneous sample. The procedure is repeated for the following approximate gravimetric water contents: 1.5%, 5%, 7%, 11%, and 15%. For Phase II, the cables used to connect the probes to the 1502B are constructed so that the probe would not have to be removed from the soil when the cable lengths were changed. Therefore, the five moisture contents are the same for all cable lengths within each soil type.

Compacted Native Soil

Throughout the calibration procedure, field conditions are simulated as close as reasonably possible. Therefore, samples of each of the soils are taken from their respective stockpiles at the construction site and are sieved with a number 4 sieve. The resulting soil is then placed in the mold with three equal lifts. As that the customized mold is of an unusual size and shape, tests are conducted to determine the number of blows required from a Standard Proctor hammer in order to achieve 95% compaction; the result is 256 blows per lift. The TDR probe is placed in the mold in the middle of the second lift. Once compaction is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. After ten L_a/L values are recorded by the CR10, the soil sample is weighed. Once the ten values are collected, the soil sample is broken apart, and a sample of soil is taken from around the probes and is dried to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil is mixed again to achieve a homogeneous sample. The procedure is repeated for the following approximate gravimetric water contents: 1.5%, 5%, 7%, 11%, and 15%. For Phase II, the cables used to connect the probes to the 1502B are constructed so that the probe would not have to be removed from the soil when the cable lengths are changed. Therefore, the five moisture contents are the same for all cable lengths within each soil type.

Uncompacted Native Soil

A similar procedure is repeated for the uncompacted native soil in Phase II as in Phase I. Samples of soil are taken from the stockpile in the field and are sieved with a number 4 sieve. The soil is place in the mold with three lifts. The TDR probe is placed in the mold in the middle of the second lift. Each lift receives 200 blows with a Standard Proctor Hammer to simulate field conditions. Once "compaction" is complete, the excess soil is shaved from the top of the mold so that the height of soil in the mold is level with the top of the mold. Ten L_a/L values are recorded by the CR10, and then the soil sample is weighed. The soil sample is then broken apart, and a sample of soil is taken from around the probes and dried to determine gravimetric moisture content of the soil per ASTM D4643. Water is then added to the soil, and the soil is mixed again to achieve a homogeneous sample. The procedure is repeated for the following approximate gravimetric water contents: 1.5%, 5%, 7%, 11%, and 15%. For Phase II, the cables used to connect the probes to the 1502B are constructed so that the probe would not have to be removed from the soil when the cable lengths are changed. Therefore, the five moisture contents are the same for all cable lengths within each soil type.

Equation Derivation

The first step in developing the equations is to convert the data into volumetric soil moisture contents (See Appendix B). The gravimetric moisture content, total mass of the sample, and volume of the sample are known variables, the volumetric moisture content is therefore determined from the following equation:

$$\theta_v = \frac{wM_t}{(1+w)V_t}$$

where: θ_v = Volumetric Moisture Content

w = Gravimetric Moisture Content

M_t = Total Mass of Sample

V_t = Total Volume of Sample (Mold)

Once the volumetric moisture content for all of the tests is calculated, the ten L_a/L values recorded by the CR10 are averaged for each moisture level. The five volumetric water contents are plotted against the resulting average L_a/L value for each cable length on an Excel™ spreadsheet. Using the "Insert Trend Line" feature on Excel, a third order polynomial is found to be the best fit for the data (See Appendix A). After a polynomial for each individual cable length is determined, the data from all of the cable lengths in each soil type is plotted on one graph to verify that separate equations are required for the various cable lengths. Upon examination, the data on the plot containing all of the ratios from the various cable lengths is more scattered than on the plots for individual cable lengths; therefore, the third order polynomial that fit all of the data does not have as high a correlation as the polynomials that fit the data for individual cable lengths. It is therefore apparent that separate polynomials are required for the five different cable lengths in the majority of the soils. The sand, however, only requires two equations: one for the shortest cable and another for the remaining four lengths in Phase I. In Phase II, only one equation is required for sand. The remaining soils require five separate equations. The resulting equations allow for the determination of the volumetric moisture content of the various soils throughout the test plots for the Alternative Landfill Cover Demonstration.

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Conclusion

TDR probes are a key element in the comparison of the six test plots in the Alternative Landfill Cover Demonstration. However, the probes must be calibrated for their specific type of soil and cable length in order to obtain useful data from the TDR measurements. When calibration is complete, the TDR probes provide a reliable measurement of in-situ volumetric moisture content of the soils that are used throughout the Alternative Landfill Cover Demonstration.

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Appendix A

Plots of Third Order Polynomials for Individual Cable Lengths

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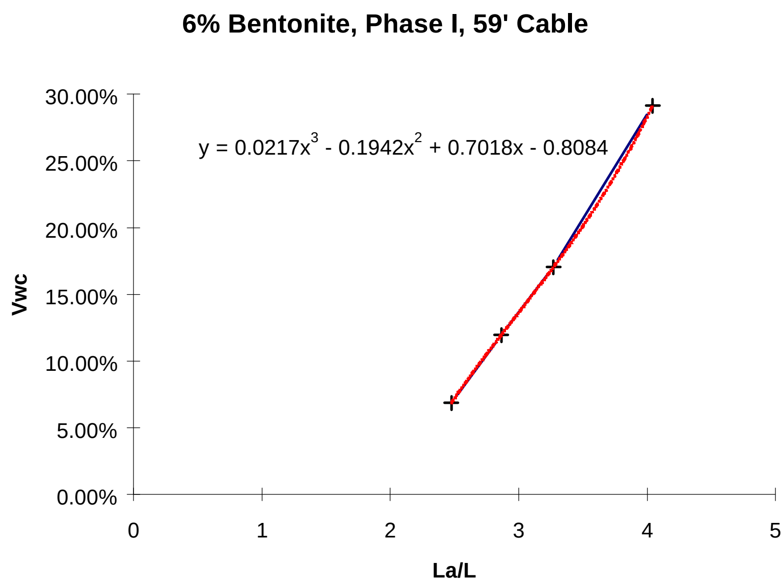

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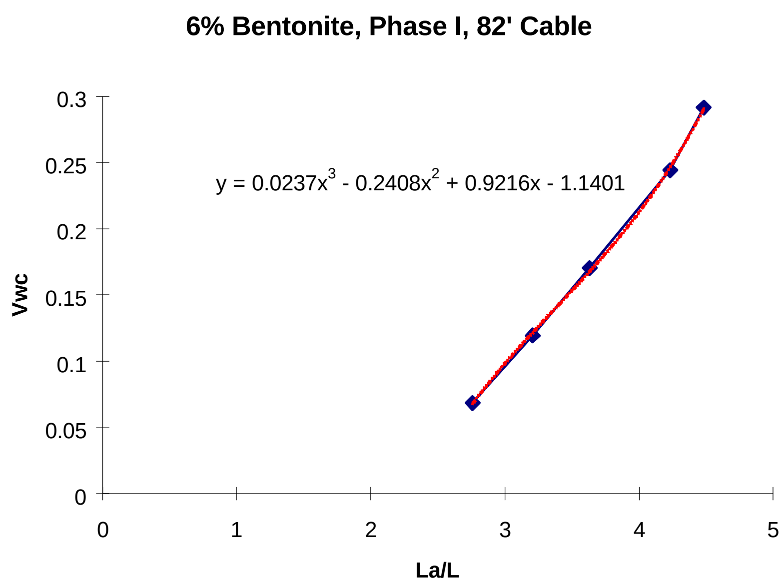

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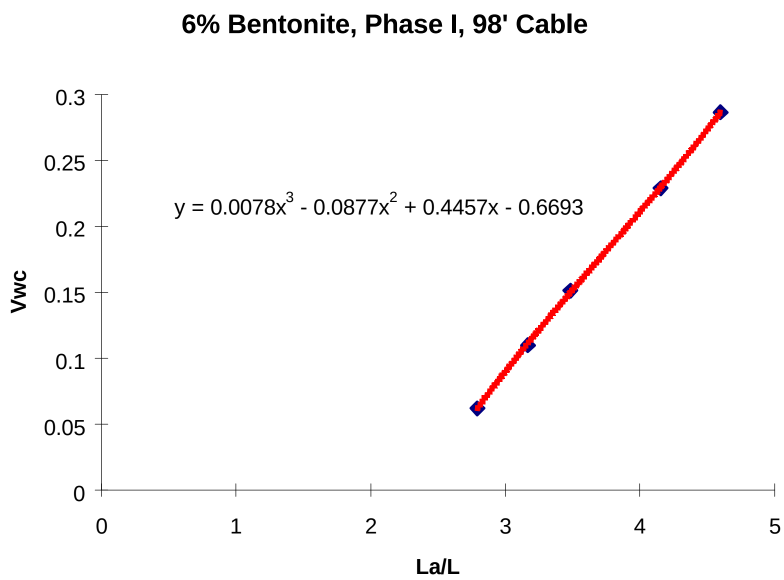

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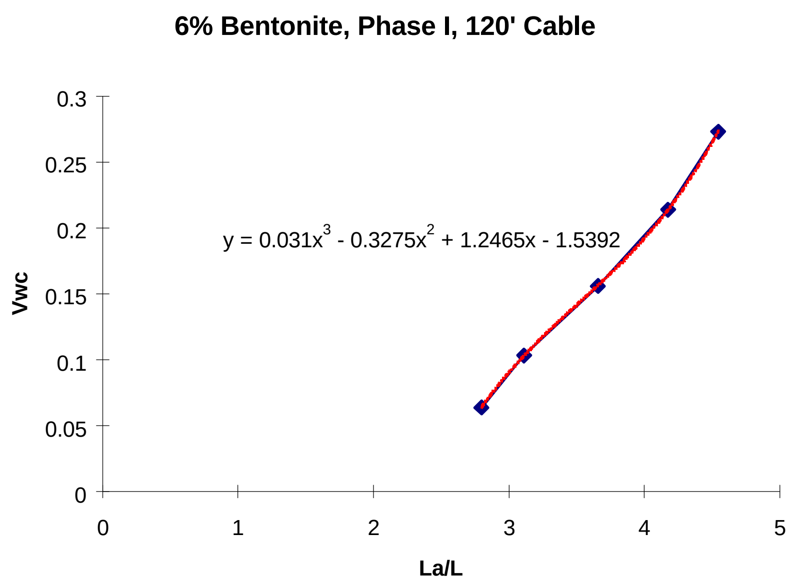

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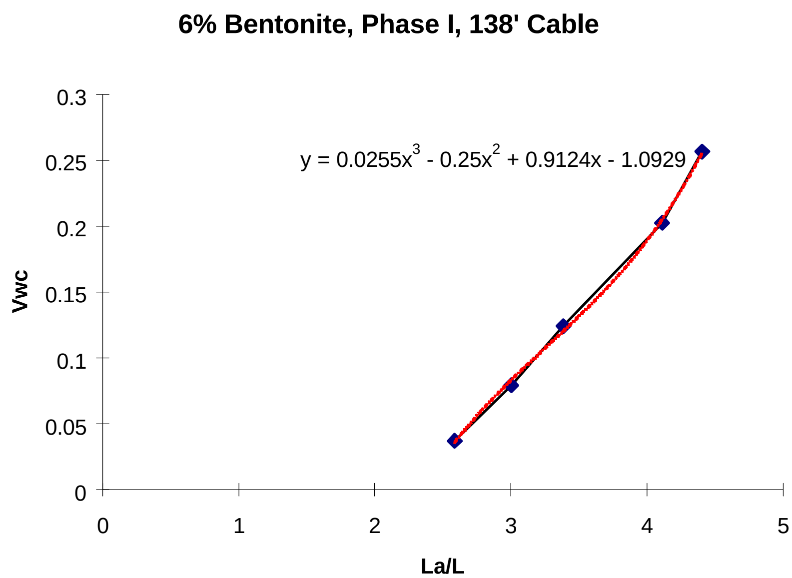

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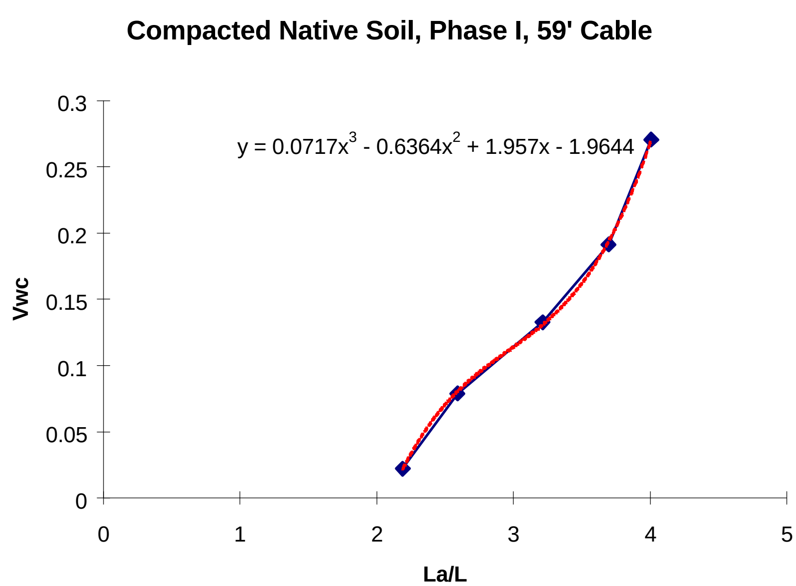

Figure A-6

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Compacted Native Soil, Phase I, 82' Cable

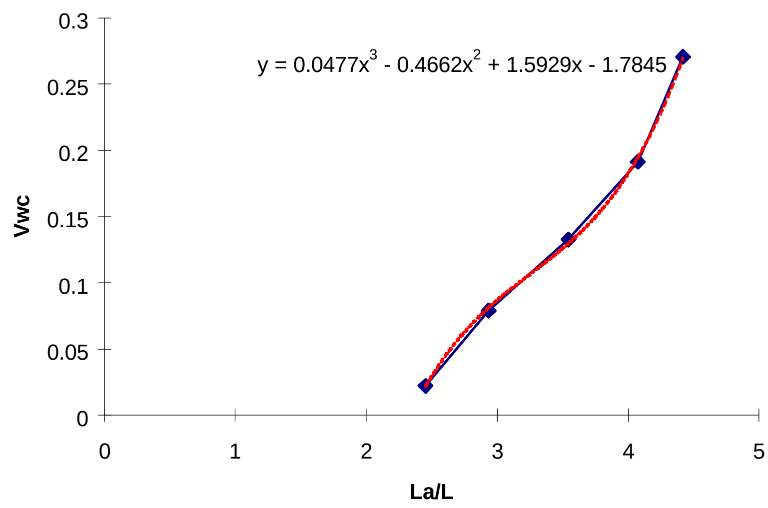
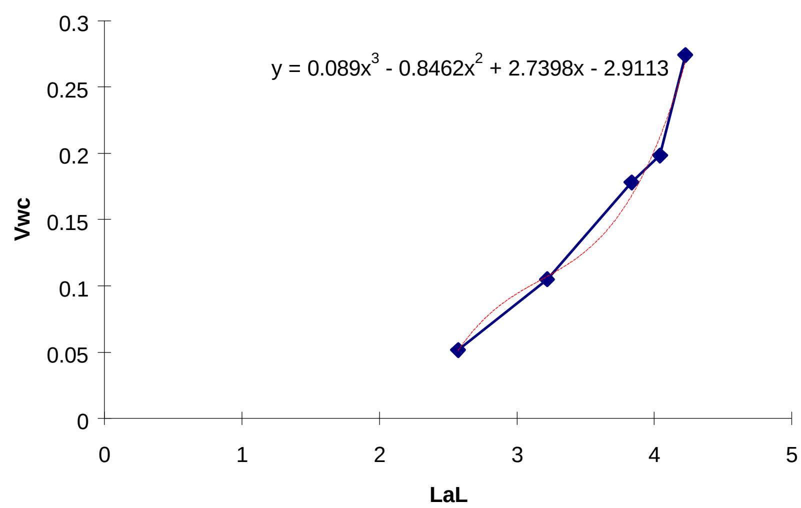


Figure A-7

Compacted Native Soil, Phase I, 98' Cable



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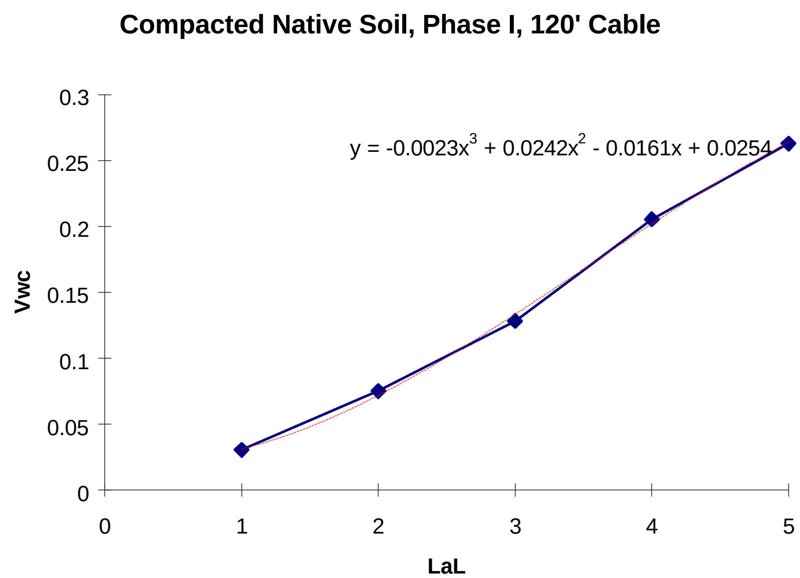

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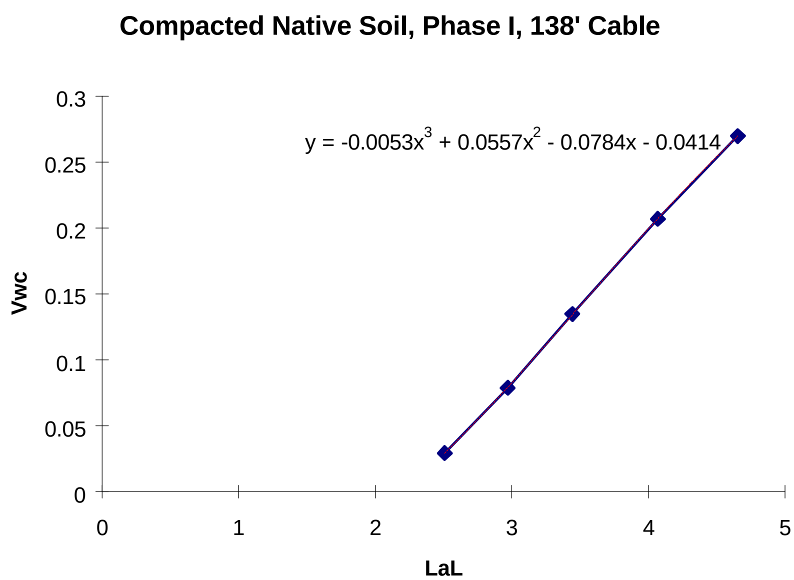

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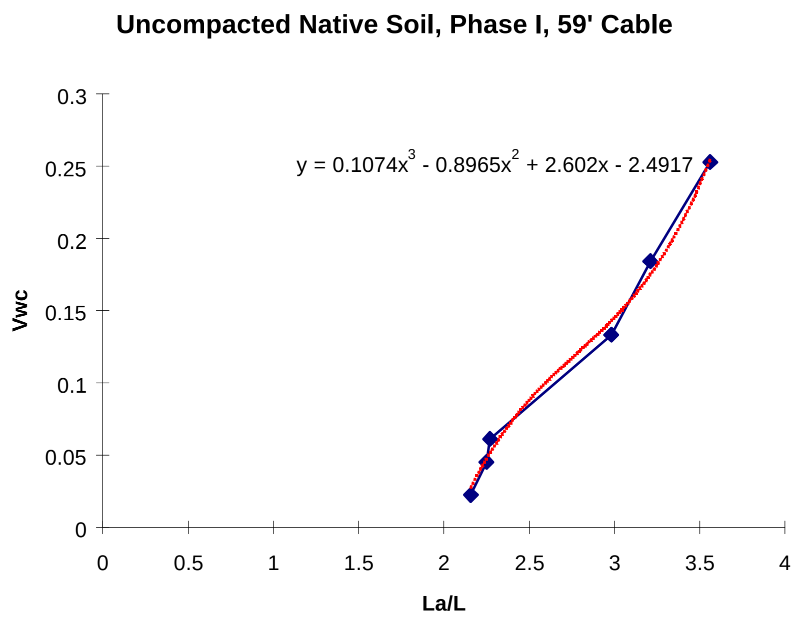

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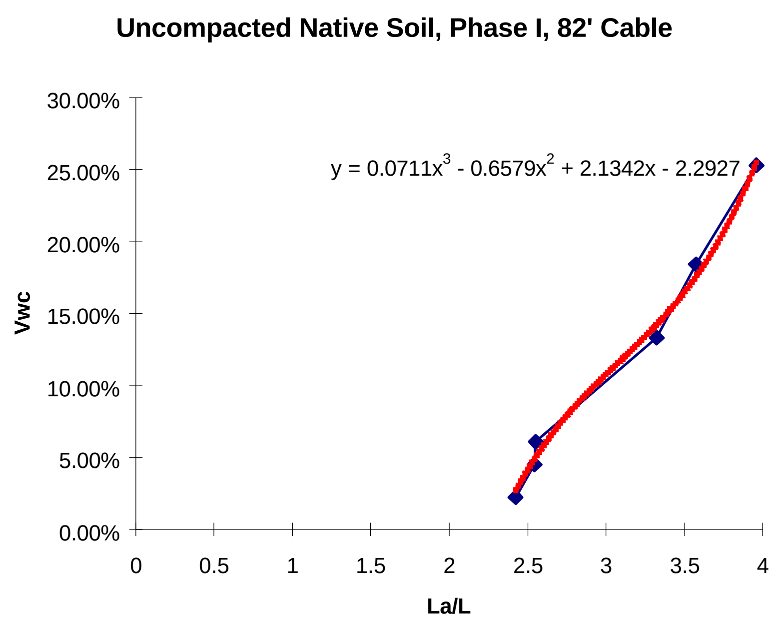

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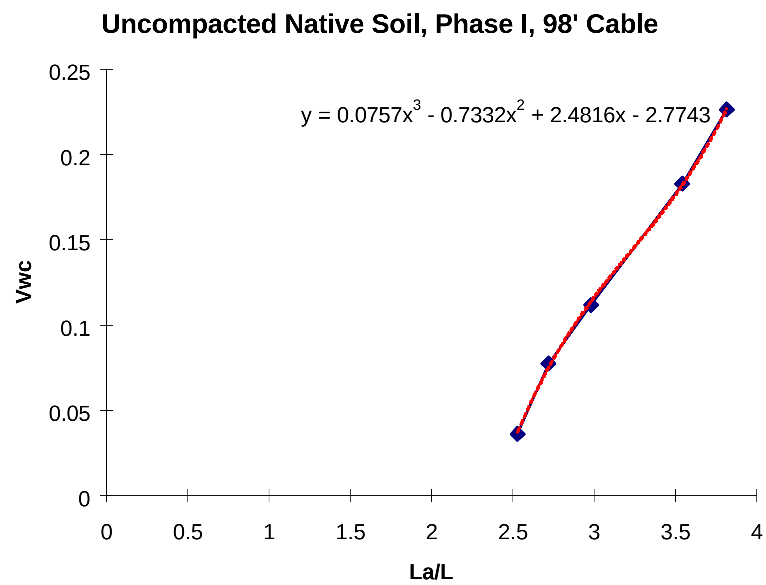

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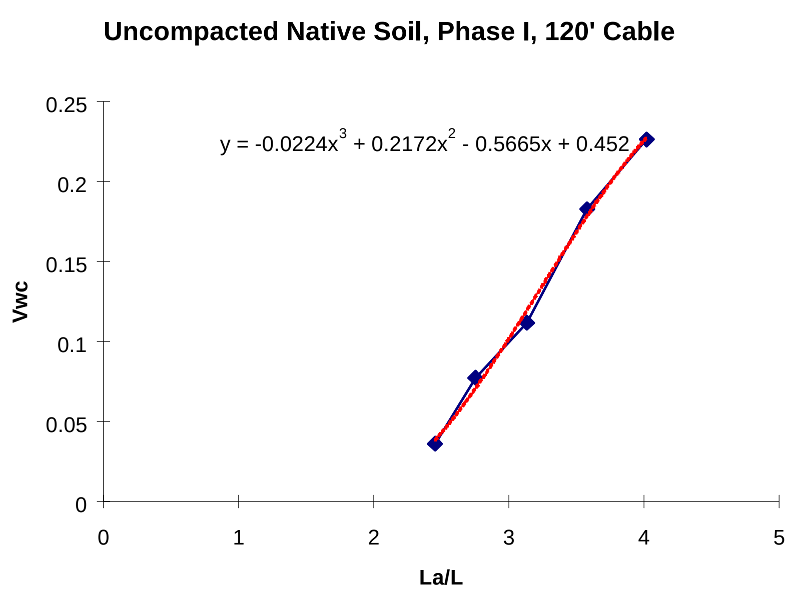

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Uncompacted Native Soil, Phase I, 138' Cable

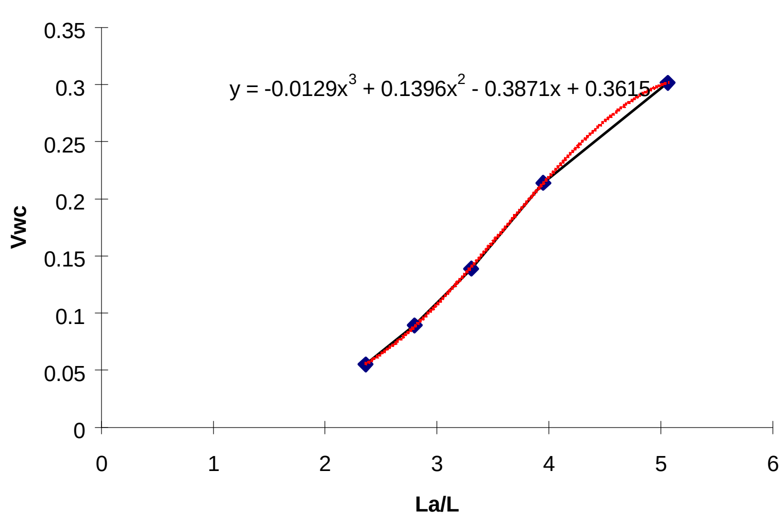
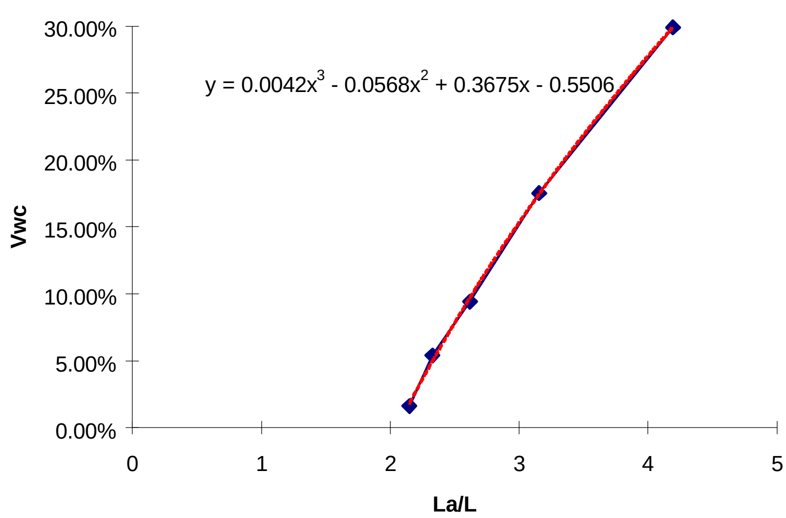


Figure A-15

Sand, Phase I, Short Cables



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Sand, Phase I, Long Cables

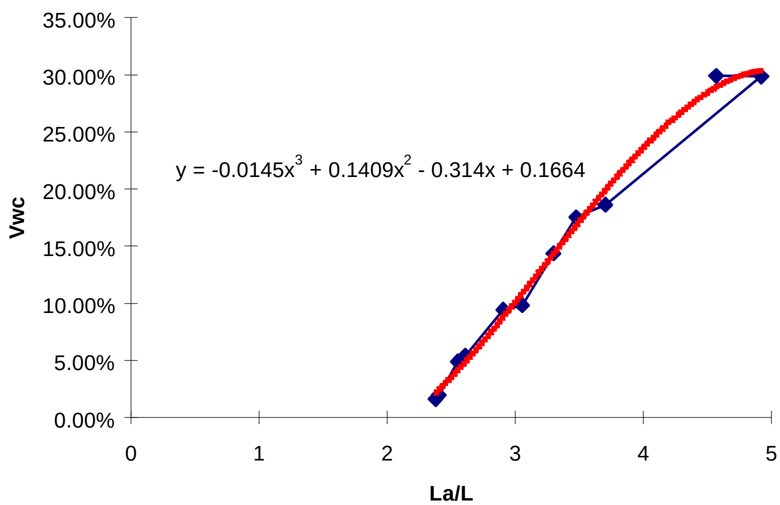
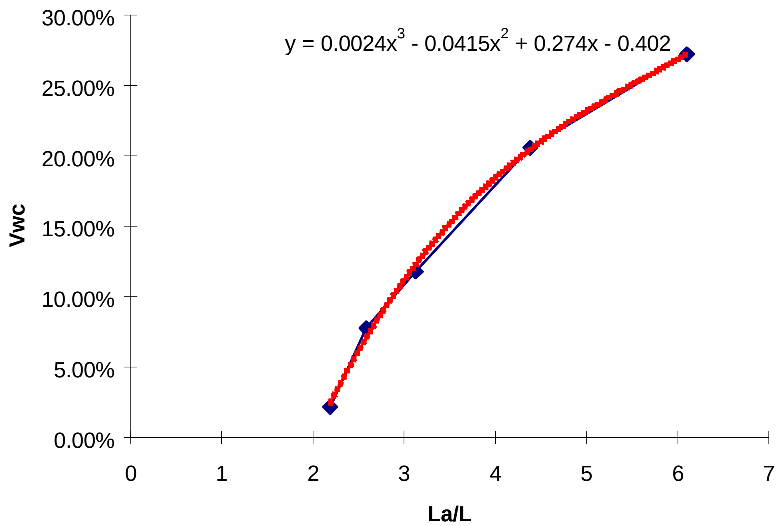


Figure A-17

Compacted Native Soil, Phase II, 85' Cable



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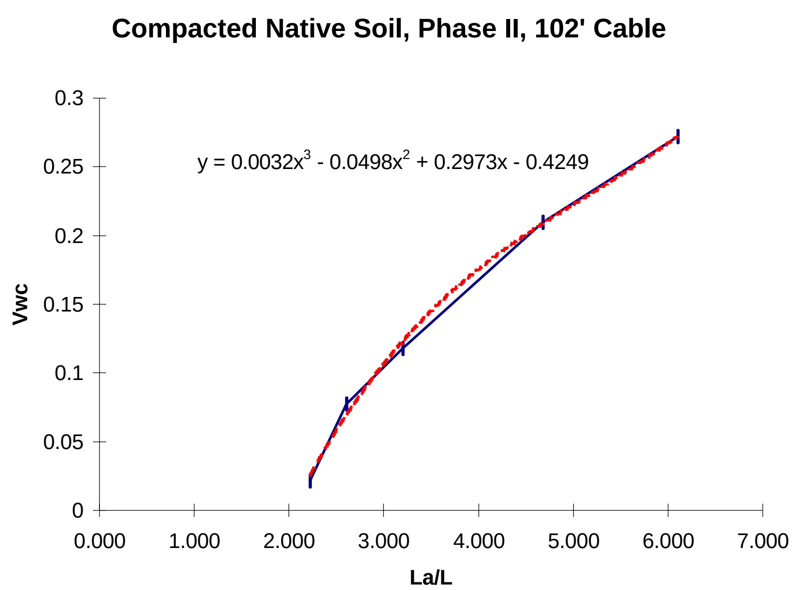
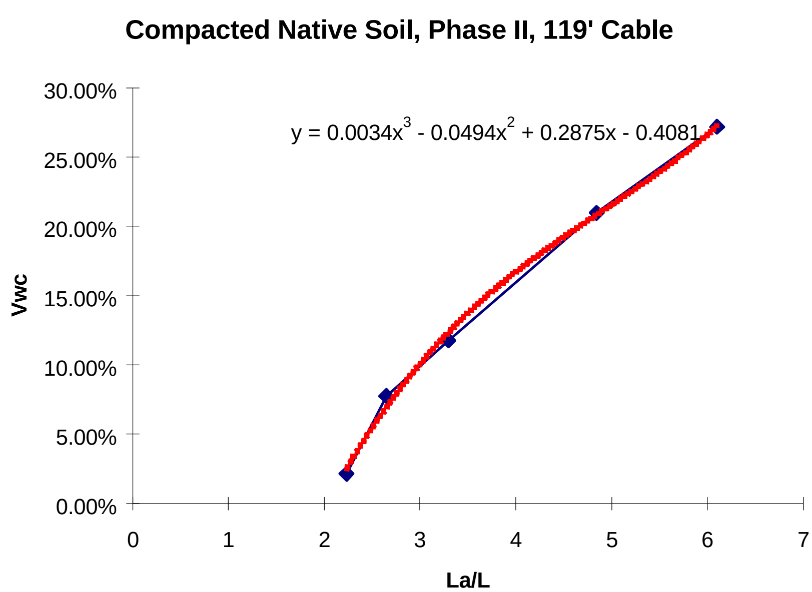


Figure A-19



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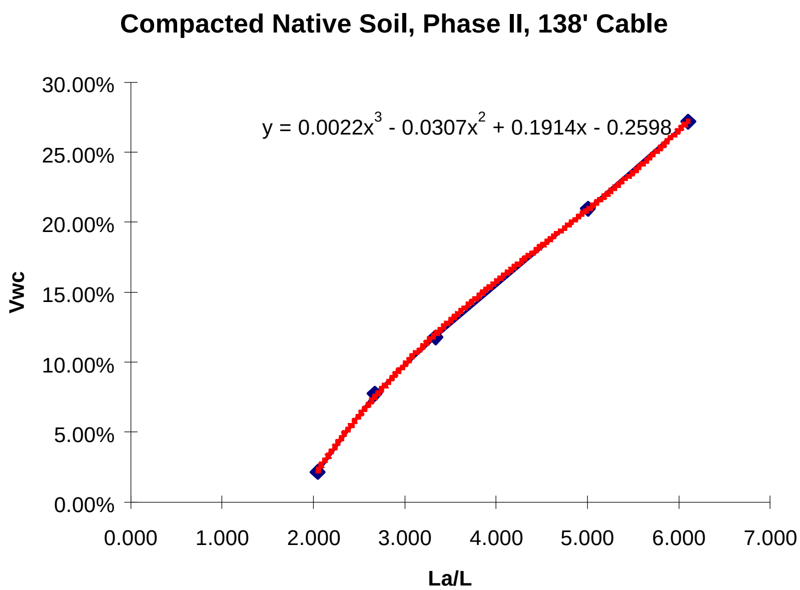

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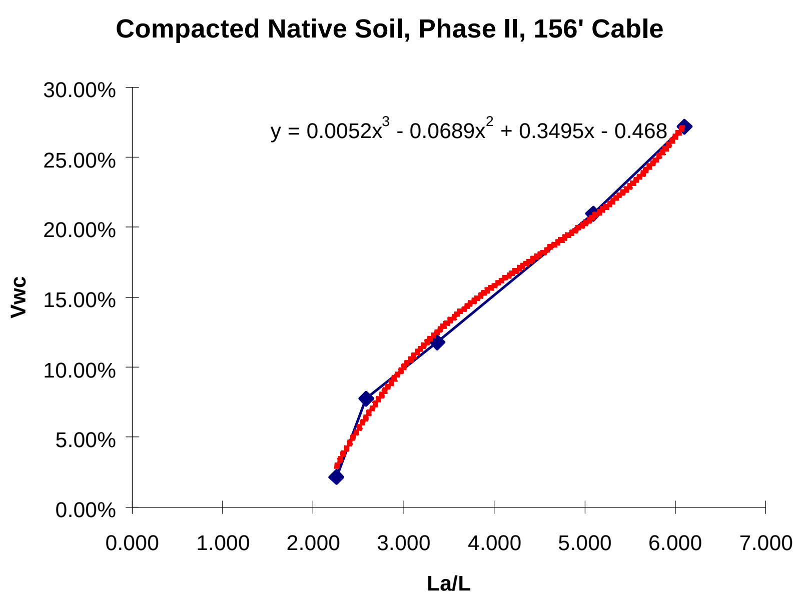

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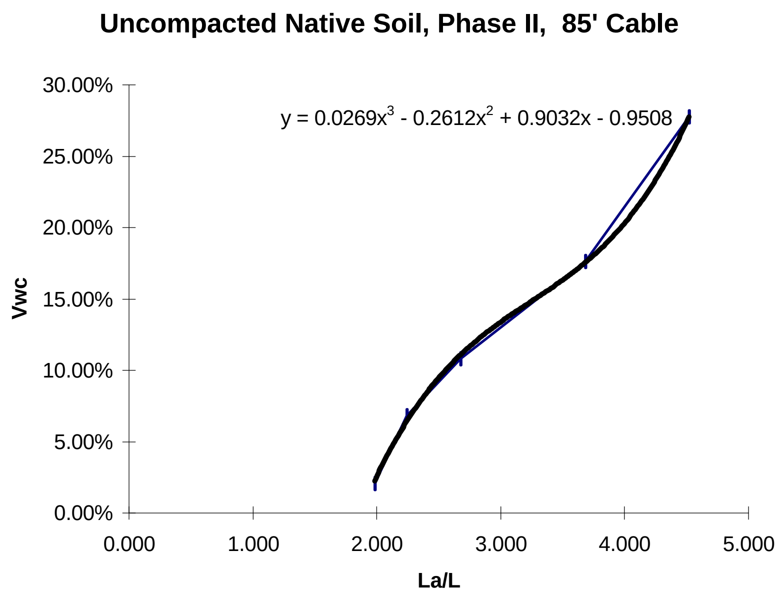

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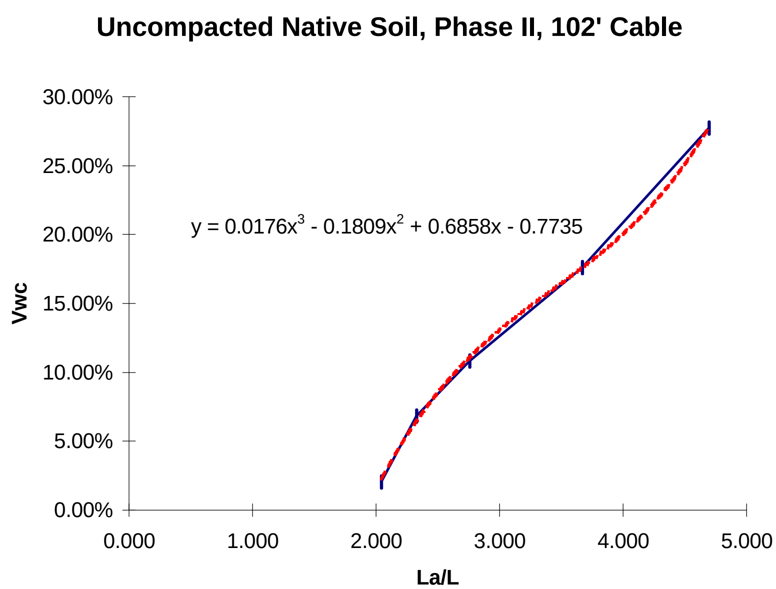

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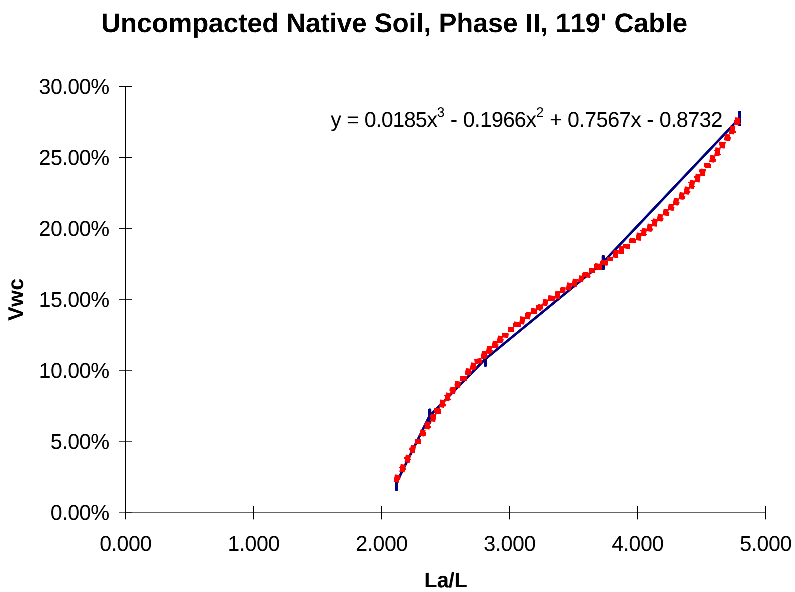

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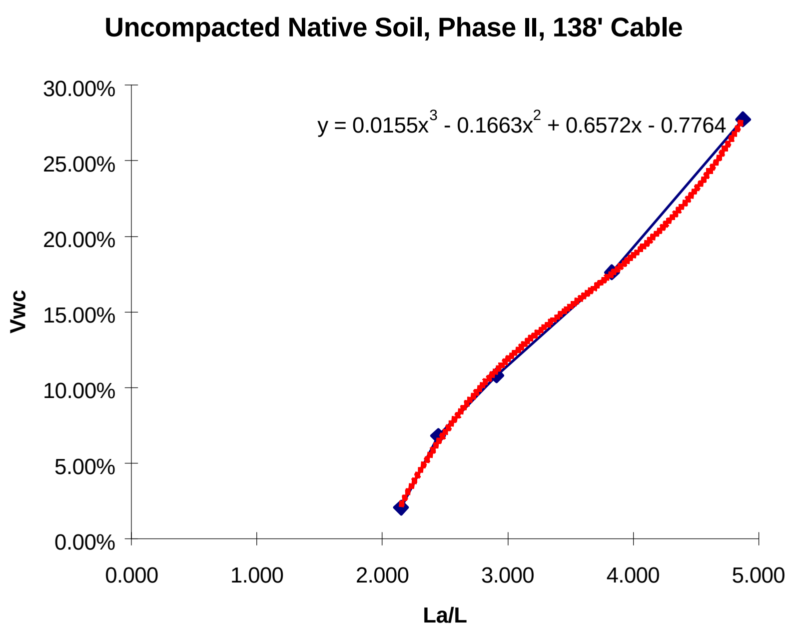

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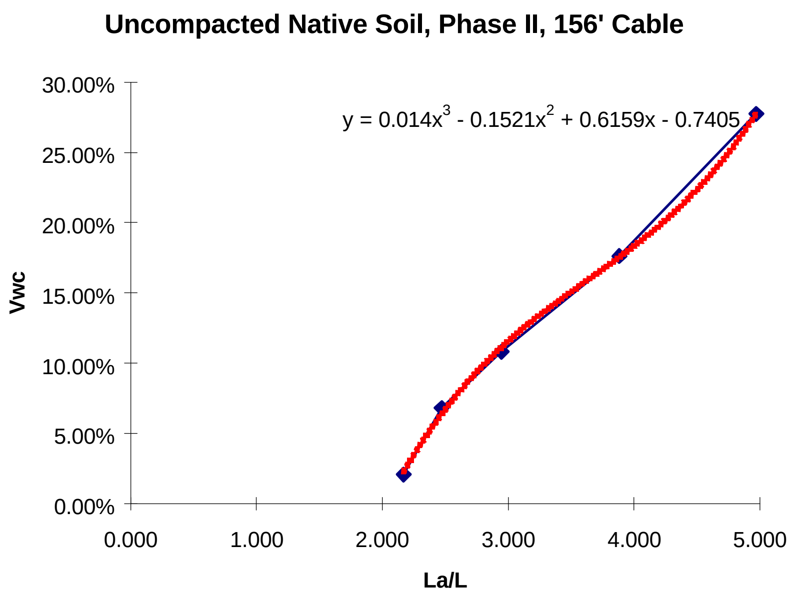

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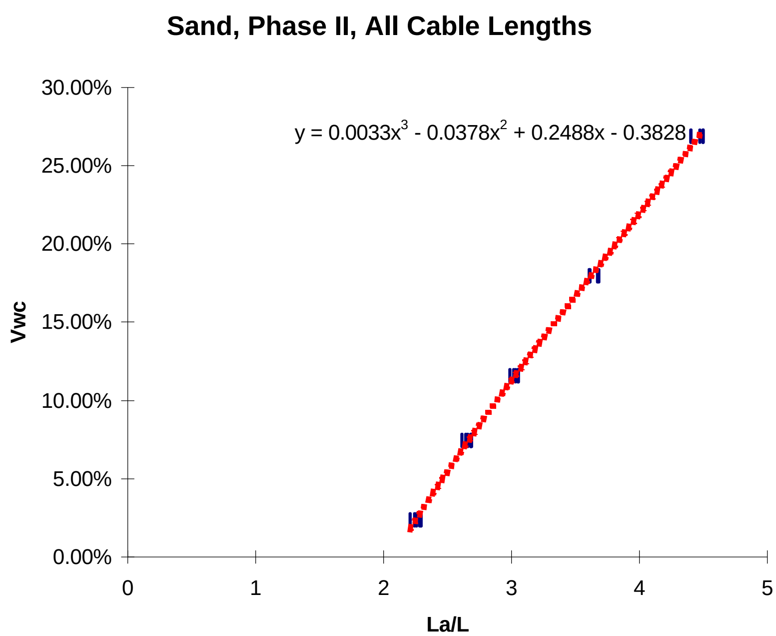

Figure A-28

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Appendix B

Volumetric Moisture Content Calculations

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Table B1: Moisture Content for Phase 1 Probe, 138' Cable, 6% Bentonite

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
125.2	122.4	2.29%	15.25	6713.24	150.14	3.70%
209	199	5.03%	15.3	6735.92	322.29	7.94%
125.1	116.6	7.29%	16.81	7420.85	504.21	12.42%
80	71.9	11.27%	18.35	8119.39	822.09	20.26%
198.3	173.5	14.29%	18.8	8323.51	1040.96	25.65%

Table B2: Moisture Content for Phase 1 Probe, 59' Cable, 6% Bentonite

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
157.4	150.8	4.38%	15.08	6636.124467	278.26	6.86%
95.4	89	7.19%	16.38	7225.800599	484.75	11.94%
155.2	140.8	10.23%	16.88	7452.599111	691.48	17.04%
126.5	110.7	14.27%	17.94	7933.411957	990.89	24.42%
209.4	179.3	16.79%	18.59	8228.250023	1182.76	29.14%

Table B3: Moisture Content for Phase 1 Probe, 82' Cable, 6% Bentonite

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
157.4	150.8	4.38%	15.08	6636.12	278.26	6.86%
95.4	89	7.19%	16.38	7225.80	484.75	11.94%
155.2	140.8	10.23%	16.88	7452.60	691.48	17.04%
126.5	110.7	14.27%	17.94	7933.41	990.89	24.42%
209.4	179.3	16.79%	18.59	8228.25	1182.76	29.14%

Table B4: Moisture Content for Phase 1 Probe, 98' Cable, 6% Bentonite

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
197.7	190.4	3.83%	15.52	6835.71	252.41	6.22%
92.7	86.9	6.67%	16.15	7121.47	445.57	10.98%
122.9	112.8	8.95%	16.93	7475.28	614.32	15.14%
132.6	116.9	13.43%	17.75	7847.23	929.12	22.89%
189.8	163.6	16.01%	19.01	8418.76	1162.13	28.64%

Table B5: Moisture Content for Phase 1 Probe, 120' Cable, 6% Bentonite

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
127.4	122.6	3.92%	15.61	6876.53	259.08	6.38%
108.6	102	6.47%	15.65	6894.67	419.01	10.32%
107.4	98	9.59%	16.4	7234.87	633.22	15.60%
125	110.8	12.82%	17.29	7638.57	867.74	21.38%
191.4	164.9	16.07%	18.1	8005.99	1108.46	27.31%

Table B6: Moisture Content for Phase 1 Probe, 59' Cable, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
145.7	143.7	1.39%	14.5	6577.16	90.28	2.22%
70.7	67.4	4.90%	15.6	6871.99	320.76	7.90%
110.1	102.3	7.62%	17.22	7606.82	538.90	13.28%
117.4	106.3	10.44%	18.56	8214.64	776.68	19.14%
231.6	200.2	15.68%	18.3	8096.71	1097.74	27.05%

Table B7: Moisture Content for Phase 1 Probe, 82' Cable, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
145.7	143.7	1.39%	14.5	6577.16	90.28	2.22%
70.7	67.4	4.90%	15.6	6871.99	320.76	7.90%
110.1	102.3	7.62%	17.22	7606.82	538.90	13.28%
117.4	106.3	10.44%	18.56	8214.64	776.68	19.14%
231.6	200.2	15.68%	18.3	8096.71	1097.74	27.05%

Table B8: Moisture Content for Phase 1 Probe, 98' Cable, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
139.5	135	3.33%	14.31	6490.97	209.39	5.16%
95	89.2	6.50%	15.85	6985.39	426.48	10.51%
126.9	115.2	10.16%	17.74	7842.69	723.09	17.82%
212.8	191.8	10.95%	18.43	8155.67	804.84	19.83%
170	146.6	15.96%	18.27	8083.10	1112.61	27.42%

Table B9: Moisture Content for Phase 1 Probe, 120' Cable, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
160.7	157.7	1.90%	14.6	6622.52	123.63	3.05%
86	82	4.88%	14.93	6568.08	305.49	7.53%
130.1	120.9	7.61%	16.68	7361.88	520.59	12.83%
152.2	136.5	11.50%	18.26	8078.56	833.33	20.53%
217.5	188.6	15.32%	18.16	8033.20	1067.40	26.30%

Table B10: Moisture Content for Phase 1 Probe, 138' Cable, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
189.2	185.8	1.83%	14.66	6649.73	119.50	2.94%
84.5	80.4	5.10%	14.99	6595.30	320.01	7.89%
143.7	133	8.05%	16.66	7352.81	547.50	13.49%
149.8	134.3	11.54%	18.34	8114.85	839.65	20.69%
213.8	185.2	15.44%	18.49	8182.89	1094.62	26.97%

Table B11: Moisture Content for Phase 1 Probe, 59' Cable, Sand

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
183.7	181.9	0.99%	15.28	6726.84	65.91	1.62%
204.5	197.7	3.44%	15	6599.84	219.46	5.41%
194.8	183.3	6.27%	14.73	6477.37	382.39	9.42%
271.7	244.3	11.22%	15.99	7048.90	710.86	17.52%
297.8	249.9	19.17%	17.09	7547.85	1214.04	29.91%

Table B12: Moisture Content for Phase 1 Probe, 82' Cable, Sand

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
183.7	181.9	0.99%	15.28	6726.84	65.91	1.62%
204.5	197.7	3.44%	15	6599.84	219.46	5.41%
194.8	183.3	6.27%	14.73	6477.37	382.39	9.42%
271.7	244.3	11.22%	15.99	7048.90	710.86	17.52%
297.8	249.9	19.17%	17.09	7547.85	1214.04	29.91%

Table B13: Moisture Content for Phase 1 Probe, 138' Cable, Sand

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
161.8	159.9	1.19%	15.47	6813.03	80.00	1.97%
141.1	136.7	3.22%	14.5	6373.04	198.73	4.90%
223.1	209.9	6.29%	15.33	6749.52	399.34	9.84%
192.4	175.8	9.44%	15.35	6758.60	583.12	14.37%
284.4	253.7	12.10%	15.89	7003.54	756.01	18.63%
279.7	234	19.53%	16.8	7416.31	1211.75	29.86%

Table B14: Moisture Content for Phase 1 Probe, 59' Cable, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
136.8	134.8	1.48%	13.68	6205.21	90.72	2.24%
175.6	167.8	4.65%	12.29	5574.71	247.62	6.10%
96	90.4	6.19%	12.09	5483.99	319.90	7.88%
118.2	108.7	8.74%	14.83	6726.84	540.65	13.32%
178.9	160.1	11.74%	15.68	7112.40	747.42	18.42%
246.9	213.7	15.54%	16.83	7634.04	1026.53	25.29%

Table B15: Moisture Content for Phase 1 Probe, 82' Cable, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
136.8	134.8	1.48%	13.68	6205.21	90.72	2.24%
175.6	167.8	4.65%	12.29	5574.71	247.62	6.10%
96	90.4	6.19%	12.09	5483.99	319.90	7.88%
118.2	108.7	8.74%	14.83	6726.84	540.65	13.32%
178.9	160.1	11.74%	15.68	7112.40	747.42	18.42%
246.9	213.7	15.54%	16.83	7634.04	1026.53	25.29%

Table B16: Moisture Content for Phase 1 Probe, 98' Cable, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
160.2	156.4	2.43%	13.67	6200.67	147.08	3.62%
84.4	80	5.50%	13.3	6032.84	314.51	7.75%
158.3	145.7	8.65%	12.56	5697.18	453.47	11.17%
114.3	102.5	11.51%	15.85	7189.51	742.22	18.29%
159.7	139	14.89%	15.63	7089.72	918.96	22.64%

Table B17: Moisture Content for Phase 1 Probe, 120' Cable, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
127.3	125.1	1.76%	13.46	6105.42	105.51	2.60%
110.2	104.6	5.35%	13.11	5946.66	302.19	7.45%
126	115.1	9.47%	13.29	6028.30	521.50	12.85%
209.8	186.4	12.55%	14.94	6776.74	755.84	18.62%
208.3	180.1	15.66%	16.51	7488.89	1013.86	24.98%

Table B18: Moisture Content for Phase 1 Probe, 138' Cable, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
83.9	80.3	4.48%	11.5	5216.37	223.82	5.52%
199.6	186.8	6.85%	12.48	5660.89	363.02	8.95%
127	115.5	9.96%	13.72	6223.35	563.53	13.89%
145.8	128.5	13.46%	16.14	7321.06	868.68	21.40%
208.7	175.3	19.05%	16.86	7647.65	1223.92	30.16%

Table B19: Moisture Content for Phase 2 Probe, All Cables, Compacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
170.1	168	1.25%	78.63	35667	440.33	2.15%
379.5	362.6	4.66%	78.57	35640	1587.13	7.75%
224.8	210.8	6.64%	85.41	38743	2412.82	11.77%
596	536.3	11.13%	93.48	42892	4296.40	20.97%
248.2	215.9	14.96%	95.6	42823	5572.86	27.20%

Table B20: Moisture Content for Phase 2 Probe, All Cables, Sand

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
146.3	144.3	1.39%	78.76	35800	489.41	2.39%
229.4	219.3	4.61%	76.15	34615	1524.03	7.44%
252.8	236.3	6.98%	80.00	36365	2373.51	11.58%
214.7	194.2	10.56%	84.77	38531	3679.02	17.95%
344.3	297.9	15.58%	89.89	40858	5506.28	26.87%

Table B21: Moisture Content for Phase 2 Probe, All Cables, Uncompacted Native Soil

M of Wet Soil	M of Solids	Moisture Content (w)	Total Mass (lbs)	Total Mass (g)	V of Water	Volumetric w
136.4	134.7	1.26%	74.74	33971	423.39	2.07%
148.7	142.3	4.50%	71.40	32455	1396.85	6.82%
218.3	204.4	6.80%	76.51	34775	2214.26	10.81%
189	171.5	10.20%	85.79	38997	3610.83	17.62%
256.9	222	15.72%	92.04	41837	5683.58	27.74%

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